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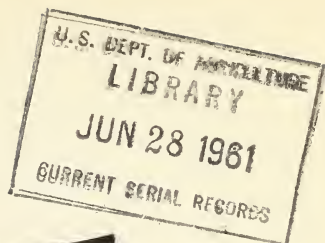
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A PROPOSED

# Site Index for Red Spruce

IN THE NORTHEAST

by **T. F. McLintock**

& **C. A. Bickford**

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# Contents

# A Key Factor

A BASIC PRINCIPLE that should be recognized at the start of any forward-looking forest-management plan is that the intensity or level of management that can be profitably applied to a given tract will be controlled largely by four factors: markets, labor supply, accessibility, and site. The more favorable these factors are, the higher the intensity of management that will be economically feasible.

The essential element of site is its relation to growth. "Just as growth is the key factor in forest management, site is the key factor in determining what the growth will be," says Spurr (1952, p. 300). In other words, within the limitations of markets, labor, and accessibility, the potential productivity of the site should dictate the level of forest management that is practical.

Very little is known about site in the spruce-fir-hardwoods region of the Northeast. Except for the scattered even-aged stands, no quantitative measure of site quality has been developed. The lack of a system for measuring site quality has been due to a considerable extent to the complexity of stand structure. Mixed, uneven-aged stands of tolerant species predominate.

Further than that, very little is known about rates of growth or probable yields, either with or without management. The information that has been available is either of a very general nature or of rather restricted applicability.

In the first category are the yield tables prepared by Westveld (1953) for cutover stands. He recognized two site classes for spruce and fir: primary and secondary softwood sites. The delineation was essentially on the basis of stand composition and in terms of the combined per-acre yield of both species rather than site index or site quality for either species. In the second category are the studies

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by Murphy (1917) and Meyer (1929), who used a series of even-aged stands occurring principally on abandoned fields or pastures.

Until records of production or yields do become available, however, it is evident that site quality must be estimated from attributes that can be measured or classified. Aside from qualitative criteria such as site indicators and descriptive classes, the most promising bases for site index are those using height growth: height at a specified age, height at maturity, or height at a given d.b.h.

The objective of the present study was to develop and test a workable, reliable technique for measuring and classifying site quality of red spruce in mature, mixed, uneven-aged stands.

# Early Philosophy

ONE OF THE EARLIEST and most significant recorded discussions of site in this country was a symposium at the annual meeting of the Society of American Foresters in 1913. The problem under consideration was that of forest land classification. It is of particular interest that the thoughts and reasoning of the group--which included men like Dana, Greeley, Munger, Pearson, and Zon--were in many cases very similar to ours today. The majority opinion was that cause and effect must be kept separate in site determinations. Site evaluation in terms of causal factors--physical features of soil and physiography and climate--was to be preferred to evaluation based wholly upon effect. Plant indicators were considered as logical criteria of site quality. But a numerical index of site was recognized as an essential tool. And it was agreed that the ultimate end in forest land classification is determination of potential producing capacity.

The basic idea of height growth as an index of site was a carry-over from European experience. Roth (1916)

pointed out that the German Association of Experiment Sta-
tions adopted total height at 100 years as a standard. Vol-
ume growth had been found subject to appreciable variations
due to stand treatment and density. Roth quotes Schwappach
that height is the factor least influenced by treatment, and
that except for a few abnormal cases, height is the best
indicator of site in stands at or beyond middle age.

In this country the use of height at a given age had
already been strongly recommended for site index by Graves
(1906). In the first comprehensive treatise on forest men-
suration to be published here, he said that under ordinary
circumstances height growth of trees is an excellent index
of the quality of a given site. "It has been proved by
repeated experiment," he said, that classification of plots
by this method and by total yield give practically the same
result.

The idea was not accepted unquestioningly (Zon, 1913;
Bates, 1918); and there was considerable sentiment in favor
of a universal site system (Roth, 1916; Watson, 1917;
Frothingham, 1921a, 1921b; Sterrett, 1921). Yet as yield
tables were developed for different species, height gradu-
ally became recognized as sufficiently sensitive to varia-
tions in soil and climate, easy to measure, and closely and
positively correlated with volume growth (Matthews, 1935,
p. 21; Bruce and Schumacher, 1935, p. 308). The system has
been used by many investigators for a variety of species:
Forbes and Bruce (1930) for southern pines, Meyer (1934) and
Hornibrook (1939) for western yellow pine, Schnur (1937) for
oaks, McArdle and Meyer (1930) for Douglas-fir, and Gevor-
kiantz and Olsen (1950) for balsam fir. Thus, height at a
given age has been established as a more or less standard
site index for even-aged stands. And almost without exept-
tion it has been limited to even-aged stands of pure, or
nearly pure, single-species composition.

In irregular stands that have a mixture of species
whose proportions vary widely, and that have an uneven-aged
stand structure, with different species attaining "maturity"
at greatly differing total ages, height in relation to age
does not reflect site quality. As Bruce and Schumacher point
out (1935, p. 335-336), "Any tree reaching maturity will
have passed through a succession of alternations between
rapid and slow growth." Red spruce is a good example of
this; as Murphy (1917) says, "The height growth of spruce
bears no definite relation to its age."

# Alternative Methods

SINCE THE conventional height-over-age approach to site index was not feasible for red spruce, a number of alternative techniques were considered. Eventually all were discarded in favor of what proved to be a very simple, yet apparently valid and reasonably workable concept: total height of dominant trees in relation to diameter at breast height.

Before presenting a discussion of this method, it might be well to review briefly the other possibilities and explain why they were not acceptable.·

## Plant Indicators

The theory of site types, generally attributed to Cajander and first developed in North America by Ilvessalo (1929), holds that certain key plants in the vegetation complex reflect site quality. This system has found favor principally in Canada, where studies have been carried out by Holman (1929), Sisam (1938), Linteau (1940), Ray (1941), Heimburger (1941) and others. The best work in this country has been in the Northeast by Heimburger (1934) and Westveld (1951).

Chief among the objections to this approach is the doubt that still remains in the minds of some authorities as to the effect of cutting and other disturbances on plant occurrences. Furthermore, considerable skill is required for consistent identification of site types, especially since abundance and local distribution of certain species are often as important as their presence. Interpretations of plant occurrence patterns must depend upon knowledge of soil and geological conditions which the average forester does not have. Even among experts, interpretation of plant indicators is subjective to a considerable extent; and in the many marginal cases encountered in the field there are chances for differences of opinion. Finally, no proved method has been developed for estimating yield from the occurrence of certain key plants.

On the basis of present knowledge of red spruce, its silvics, growth habits, and site requirements, it would be possible to draw up several site classes that make use of topographic position, slope, aspect, drainage, etc. This has actually been done by Donahue (1940) for spruce in the Adirondacks, and by Spurr for New England white pine (1952, p. 305). But this approach is very general, and it may be somewhat subjective, depending to a great extent upon the judgment and experience of the fieldman.

## Growth
## And Yield

The real criterion of site quality is, of course, the yields that can be obtained. For red spruce there was very little reliable long-time yield information available in sufficient detail to be usable. In this case yield data present a special problem because red spruce nearly always occurs in varying mixtures with several other species. Thus total yield of all species, or even of spruce and fir combined, would be doubtfully indicative of site quality for red spruce. If yield of this species is to be used, allowance will have to be made for the amount of spruce on the ground in the first place, as well as for stand density.

## Diameter
## Growth

A considerable amount of information was available on diameter growth of red spruce related to crown characteristics. It seemed possible that for a series of dominant-tree classes based on crown features, a group of growth classes might be set up that would correspond to site classes. It is probable that growth would have to be restricted to the last 20 years so as to avoid possible distorting effects of changes in crown features--particularly crown class--over a longer period. The theory would be that, with crown characteristics kept constant, variations in diameter growth would be principally manifestations of site differences.

The theory is given some support by reason of the fact that on what proved to be good sites in this study dominant trees attained larger diameters than on poor sites.

This method was not tried out  because of the unknown effect
of stand density,  and because  of the large number  of tree
classes needed to make it sufficiently sensitive.    However,
it may have some merit.


Main-Stand
Age


        Duerr and  Gevorkiantz (1938)  found that  apparently
all-aged hardwood stands  in the  Lake States  were actually
composed of three age groups.  The trees in what they called
the "main stand" made up 84 percent of the total basal area,
and ranged in age from 166 to 182 years.  The main stand was
then considered  to be  even-aged,  and the  height-over-age
approach worked very well.    The spruce-fir forests  of the
Northeast, however,  do not have this structure but are much
more irregular and are essentially all-aged.


Height Over Age
At Breast Height


        It has sometimes been suggested that much of the var-
iation in height-age relationships for tolerant species like
red spruce would be reduced  if age at breast height  rather
than total age were used.    This would eliminate the period
of very slow "juvenile" growth that occurs almost invariably
under severe suppression.    If this early stage,  up to 4.5
feet in height,  embraced most  of the suppressed period  in
the life of the tree,  then possibly height attained  when a
tree reached a  specified "breast-high" age might constitute
a satisfactory site index.

        While this approach  was tried  with some success  by
Mount and Gove (1952) for red spruce in an area near Bangor,
Maine,  it seemed desirable to check the growth pattern over
a wider geographical range. Accordingly growth-ring records
for more than 300 red spruce were examined  to determine the
extent and frequency  of periods of suppressed growth  later
in the life of the tree.    These were ring counts and radial
increment  measurements  made  during the  previous 10 years
from all over the region by the Penobscot Research Center.

        It was found that  the initial period  of suppression
and slow growth  lasted beyond 1 inch d.b.h.  for 92 percent
of the trees, and beyond 2 inches for 77 percent.    In most
cases (89 percent)  the trees went through  one to six addi-

tional suppression periods of varying length before reaching maturity.

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## Height Over Age
## For Unsuppressed Trees

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It was thought that enough dominant spruce might be found that had been "free growing" from germination. If so, the conventional height-over-age system might be imposed upon the stand even though it was essentially all-aged. A follow-up on this possibility on seven different stands was discouraging. Out of 54 trees selected as being apparently unsuppressed from seedling stage (as nearly as could be determined from local conditions) only 3 did not show one or more well-defined suppression periods lasting 17 to 69 years. From this evidence it was concluded that unsuppressed red spruce are too rare to be relied upon for site determination.

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## Height
## At Maturity

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Height finally attained by a species as growth in height gradually ceases is closely related to site quality and has been suggested by many investigators (Frothingham, 1918, 1921a; Fox and Kruse, 1939; Westveld, 1933; Bruce and Schumacher, 1935, p. 309-310; Donahue, 1940; Meyer 1940) as a measure of site quality. This is the same as the horizontal asymptote suggested by Bruce and Schumacher and the $\underline{H}$ proposed by H. Arthur Meyer; it is equally appropriate whether the abscissa is age in years or d.b.h. in inches.

In the usual stands where red spruce occurs, however, the largest dominant spruce are often immature and still showing active height growth. Thus height at maturity is a reasonable approach in theory but difficult in practice because so few red spruce are left until their height growth virtually ceases.

If height at maturity is an accurate gage of site quality, and if the curve[1] of height over d.b.h. is well described by the formula proposed by Meyer (1940), then it is logical that height at a standard d.b.h. should also be a useful index of site quality. Thus if trees on a given site mature at about the same d.b.h. and height, immature dominant trees should approach these limits along a similar pattern, and a single curve should accurately describe height over d.b.h. for a particular site. This assumes a fairly stable tree form that improves somewhat with site quality. This in turn is dependent on reasonably uniform stand density. Thus site quality might be evaluated by determining the total height and d.b.h. of the average dominant tree and comparing this average with a series of curves of height over d.b.h. by site index classes.

The function proposed by Meyer, $Y = 4.5 + h (1-e^{-aX})$, supports the foregoing argument. For a particular stand, $a$ and $h$ would be fixed and $Y$ for a mature $X$ would be height at maturity. Now if $a$ were constant for red spruce on all site qualities, it is evident that variations in $h$ would reflect variations in height at maturity and that each specific value of $h$ would have a corresponding value of $Y$, total height, for a standard $X$, d.b.h., such as 14.

It should be noted in passing that this argument is implicit in the common practice of preparing local volume tables based only on d.b.h. One of the major reasons for obtaining height-diameter curves in different stands is that site differences strongly affect height-diameter relationships (Chapman and Demeritt, 1932, p. 89).

Bruce and Schumacher point out that for the conventional site index of height over age there should be no intercorrelation of age and site quality. If d.b.h. is substituted for age, it would seem desirable that d.b.h. and site quality be independent. Other things being equal, diameter growth and d.b.h. of mature trees tend to be greater on

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[1]The parabola suggested by Ker and Smith (1955) is no doubt easier to work with than Meyer's exponential. Computations for this study were completed before publication of the Ker-Smith article. However, a parabola has the theoretical objection that, as d.b.h. is increased, height increases without limit-- which is not the way trees grow. Furthermore, their treatment of maximum height seems too subjective.

good sites than on poor sites.    But use of total height of
trees of a fixed d.b.h. is expected to satisfy this require-
ment  if trees  of the same d.b.h.  do in fact show positive
correlation between total height and site quality.

# Procedure Used

THIS STUDY  was based  upon data  obtained from 910 domi-
nant red spruce trees.  They were selected in 32 stands
well distributed  over  the  northern  two-thirds  of Maine.
Particular effort  was made  to include  as wide a range  of
sites as possible.

Height growth is sensitive to site quality.  Diameter
growth is less so;  it proceeds at a rate influenced largely
by condition and position of the crown and by stand density.
In order to reduce  to a minimum  the influence upon height-
diameter relations of factors  other than site,  certain re-
quirements  for both  the study areas  and the  sample trees
themselves were defined at the start of the test.

No stand  was selected  in which  there had been  any
cutting,  as nearly as could be determined,  within the last
25 years.  This eliminated most possibility of recent stimu-
lation of diameter growth due to release.

Stands  that  were  obviously  over- or under-stocked
were avoided.  This reduced the effect of stand density upon
diameter growth,  and it also eliminated any possible effect
upon height growth.

No discrimination was made  for or against any forest
type. It was expected that a wide range in composition would
be encountered  because the study called for sampling a wide
range of sites.

The  principal  requirement  with  respect  to  stand
structure was that it contain at least 25 red spruce over 10

inches d.b.h.--and preferably over 12 inches--in a dominant crown position.

The area as finally selected to include the sample trees was seldom less than 1 or more than 5 acres in size. Each stand that was considered was first examined, before any measuring of trees was done, to be sure that there would be no change in site for at least 2 chains beyond the edge of the sampled area. When potential sample trees were so scattered that it was necessary to go much beyond 5 acres to find 25 trees meeting the requirements of the study, some slight change in site was usually noted. In such cases the area was rejected.

In selecting the sample trees, no spruce was accepted for study unless it was a dominant and had been a dominant[2] for at least 25 years, as nearly as could be estimated. Any tree that had sustained a broken top or any other serious injury that might have affected height growth was rejected, as were trees with a crown ratio of less than 0.4 and those with crowns of very poor vigor. Wherever possible, trees were selected so as to provide a 6-inch range in diameter. In no case was any tree smaller than 9.6 inches d.b.h. selected.

The diameter of each tree was measured at breast height with a diameter tape and recorded to the nearest 1/10-inch. Total height was measured with an Abney level to the nearest foot. Several trees in each stand were measured twice, from different directions, as a check against the accuracy of the height determinations. All doubtful cases were also measured twice.

In addition to the measurements, each tree was given a number on the tally sheet, and a paper tag carrying the corresponding number was stapled to the tree. This procedure was to permit checking any apparently discrepant measurements later on if necessary.

Each stand was described with respect to forest type, topographic position, aspect, and degree of slope. The

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[2]For the uneven-age stands with which this study was concerned, a 'dominant' tree was defined as follows: a tree whose crown is above the general level of the canopy and obtains full light from above. The upper portion of the crown is also getting light from the sides. It dominates the surrounding stand, so crown competition with adjacent trees is confined to the lower half or at most the lower two thirds of its crown.

floristic type was also recorded. The location of each tract was marked on a map and the directions for reaching it were recorded.

# Results

THE OBJECTIVE of this study was to develop a means of estimating site quality in numerical terms from the measurement of a relatively small sample of trees. The method would have to be simple and easy to use, and would have to accurately reflect variations from one place to another in the capacity to grow wood, specifically wood of red spruce.

### Developing A Gage Of Site Index

Meyer's (1940) proposed mathematical expression for height curves, cited in a preceding section, gave a starting point. An equation of this form was fitted to the tree-measurement data described above, using averages by d.b.h. classes. The method of least squares was used with averages of height by d.b.h. classes, pooling all the data. Should d.b.h. be correlated with site quality, this pooling could lead to overestimation of the slope of the curve.

It was then argued that if site affected the relationship of height to diameter, the general shape of the curve would be unchanged,[3] but the entire curve would be raised or lowered accordingly, retaining a fixed point: d.b.h. = 0, height = 4.5. Thus as site quality increased or decreased, a family of curves could be obtained, having a fixed point in common. These curves would pass through a

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[3]This would be true with $a$ constant while $h$ might vary with site. On the other hand, a constant $h$ and variable $a$ results in significant changes in the shape of the curve.

Table 1.--Height of dominant red spruce in the Northeast, in feet, by diameter and site index

| D.b.h. (inches) | Site index | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | 52 | 54 | 56 | 58 | 60 | 62 | 64 | 66 | 68 | 70 | 72 | 74 | 76 |
| 10 | 42.4 | 44.1 | 45.7 | 47.4 | 49.1 | 50.7 | 52.4 | 54.1 | 55.7 | 57.4 | 59.1 | 60.7 | 62.4 | 64.1 |
| 11 | 44.6 | 46.3 | 48.1 | 49.9 | 51.6 | 53.4 | 55.2 | 56.9 | 58.7 | 60.4 | 62.2 | 64.0 | 65.7 | 67.5 |
| 12 | 46.6 | 48.4 | 50.3 | 52.1 | 54.0 | 55.8 | 57.7 | 59.5 | 61.4 | 63.2 | 65.1 | 66.9 | 68.8 | 70.6 |
| 13 | 48.4 | 50.3 | 52.2 | 54.2 | 56.1 | 58.0 | 60.0 | 61.9 | 63.8 | 65.7 | 67.7 | 69.6 | 71.5 | 73.5 |
| 14 | 50.0 | 52.0 | 54.0 | 56.0 | 58.0 | 60.0 | 62.0 | 64.0 | 66.0 | 68.0 | 70.0 | 72.0 | 74.0 | 76.0 |
| 15 | 51.6 | 53.6 | 55.7 | 57.8 | 59.8 | 61.9 | 64.0 | 66.0 | 68.1 | 70.2 | 72.2 | 74.3 | 76.4 | 78.4 |
| 16 | 52.9 | 55.0 | 57.1 | 59.2 | 61.4 | 63.5 | 65.6 | 67.7 | 69.9 | 72.0 | 74.1 | 76.2 | 78.4 | 80.5 |
| 17 | 54.1 | 56.3 | 58.5 | 60.6 | 62.8 | 65.0 | 67.2 | 69.4 | 71.6 | 73.7 | 75.9 | 78.1 | 80.3 | 82.5 |
| 18 | 55.2 | 57.5 | 59.7 | 61.9 | 64.1 | 66.4 | 68.6 | 70.8 | 73.1 | 75.3 | 77.5 | 79.8 | 82.0 | 84.2 |
| 19 | 56.2 | 58.5 | 60.8 | 63.0 | 65.3 | 67.6 | 69.9 | 72.1 | 74.4 | 76.7 | 79.0 | 81.2 | 83.5 | 85.8 |
| 20 | 57.2 | 59.5 | 61.9 | 64.2 | 66.5 | 68.8 | 71.1 | 73.4 | 75.8 | 78.1 | 80.4 | 82.7 | 85.0 | 87.3 |
| 21 | 58.1 | 60.5 | 62.8 | 65.2 | 67.5 | 69.9 | 72.2 | 74.6 | 77.0 | 79.3 | 81.7 | 84.0 | 86.4 | 88.7 |
| 22 | 58.8 | 61.2 | 63.6 | 66.0 | 68.4 | 70.8 | 73.2 | 75.6 | 77.9 | 80.3 | 82.7 | 85.1 | 87.5 | 89.9 |
| 23 | 59.5 | 61.9 | 64.4 | 66.8 | 69.2 | 71.6 | 74.0 | 76.5 | 78.9 | 81.3 | 83.7 | 86.1 | 88.5 | 91.0 |
| 24 | 60.2 | 62.7 | 65.1 | 67.6 | 70.0 | 72.5 | 74.9 | 77.3 | 79.8 | 82.2 | 84.7 | 87.1 | 89.6 | 92.0 |
| 25 | 60.8 | 63.2 | 65.7 | 68.2 | 70.7 | 73.1 | 75.6 | 78.1 | 80.6 | 83.0 | 85.5 | 88.0 | 90.4 | 92.9 |

series of values  of total height of trees  at any specified
d.b.h.,  which would then identify  the suggested site-index
values.   A diameter of 14 inches was selected as the stand-
ard d.b.h. at which site-index values would be read.

The general equation is

$$Y = 4.5 + h\ (1 - e^{-aX})$$

in which $Y$ is total height in feet; $X$ is d.b.h. in inches; $h$
and $a$ are parameters determined from the data;  and $e$ is the
base of  natural logarithms.    In the  fitted equation  h =
80.316 and a = 0.094.  The family of curves is obtained, as-
suming that:  (1) the curve of total height over d.b.h.  for
dominant red spruce has a constant $a$ of 0.094; and (2) vari-
ations  in site quality  affect only  the $h$  of the  general
equation.

A series of values for $h$ were calculated from

$$h = \frac{Y - 4.5}{1 - e^{-aX}}$$

in which $Y$ was taken as  50, 52, 54, ... and 76 feet succes-
sively.  In this expression $X$ is 14 inches, thus

$1 - e^{-aX} = 1 - e^{-0.094\ (14)} = 0.732$, and h = (Y - 4.5)/0.732.

For each value of $h$ there is a series of  heights over diam-
eter for the corresponding site index. The resulting average
heights, by d.b.h. and site index, appear in table 1.    The
data in this table  are also shown as figure 1,  which looks
like the conventional  site-index  curves  except  that  the
abscissa is d.b.h. rather than age.

Site Index
Of A Stand

To determine site index of a stand,  it is  necessary
to measure  a sample of dominant red spruce trees and deduce
a site index  from the data.    The easiest procedure is  to
obtain averages  of height and diameter  and  read  the site
index from the curves of figure 1. This procedure is accept-
able if no systematic errors are introduced.  It is evident,
however,  that if the original formula  accurately describes
the relationship of height to diameter, averages are certain
to result in bias: the relationship is curvilinear and there

# PROPOSED SITE INDEX FOR RED SPRUCE
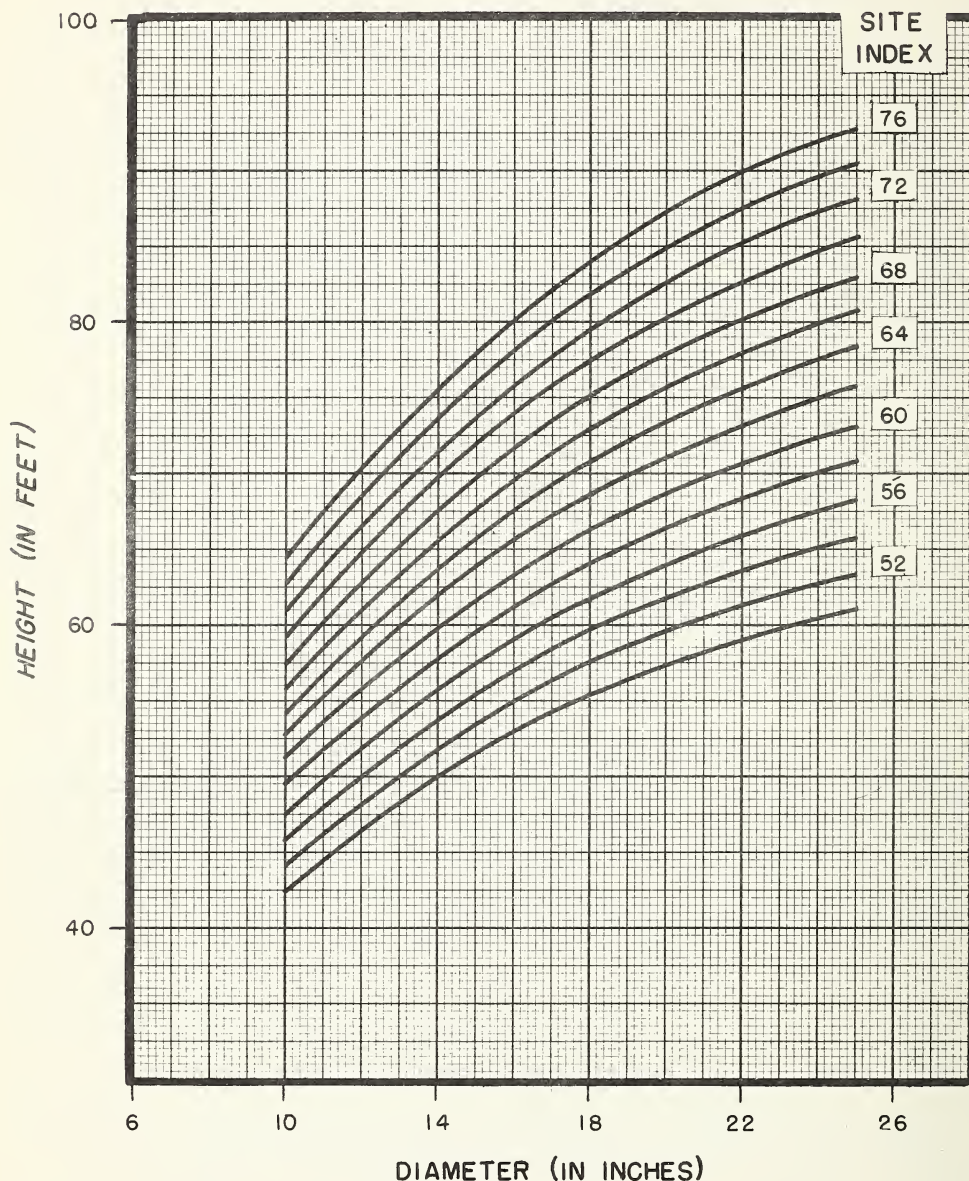## MANY — AGED STANDS
### MAINE, 1955



FIGURE 1.--Curves for determining site index of a stand. Averages of height and diameter are obtained from a sample of dominant spruce trees. These are plotted on the graph and the site index is read off the curve.

is no change in the direction of curvature.  Variation among trees  of the  same stand  is bound to exist,  and it may be great enough to obscure this bias.

Thus the accurate procedure  is to estimate  the site index for each tree,  using its measurements and reading the value from the curves of figure 1, as described above. These individual  tree estimates  are then  averaged  to obtain  a site-index figure for the stand.

If still greater accuracy is important,  superior re-sults  can be obtained  by using  the foregoing formula  re-arranged to

$$h = \frac{Y - 4.5}{1 - e^{-0.094X_1}}$$

Then site index is

$$4.5 + h \left[ 1 - e^{(-0.094)\,(14)} \right] = 4.5 + h(0.732)$$

or

$$4.5 + (0.732)\; \frac{Y_1 - 4.5}{(1 - e^{-0.094X_1})}$$

where $X_1$ and $Y_1$ are  corresponding measurements  or averages of d.b.h. and  total height.  Table 2 has been prepared to make this determination easier.  This table shows values of $(1 - e^{-0.094X})$ by tenth inches of d.b.h.  from 10.0 to 25.9.

Now to estimate site index for any stand:

1.  Subtract 4.5 from the measured total height of each tree.
2.  Read $(1 - e^{-aX})$ from table 2 for the measured d.b.h., X.
3.  Divide  the difference  obtained in step 1  by the value for $(1 - e^{-aX})$ of step 2.
4.  Multiply this quotient by $(1 - e^{-14a}) = 0.732$.
5.  Add 4.5  to this product  to obtain  the  estimated site index.

This procedure is illustrated in table 3,  using both individual tree data and plot averages.  The result of aver-aging site index, 63.48,  is compared with the site index of the tree of average height and d.b.h., 63.07. The associated standard error of the mean is 0.786 foot. Thus it is evident that for this stand the bias mentioned earlier is trivial in

Table 2.—Values of $(1-e^{-aX})$ where $a = 0.094$, for diameters $(X)$ of 10.0 to 25.9

| D.b.h. (inches) | Tenths of inches of diameter | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | 0.609 | 0.613 | 0.617 | 0.620 | 0.624 | 0.627 | 0.631 | 0.634 | 0.638 | 0.641 |
| 11 | .644 | .648 | .651 | .654 | .658 | .661 | .664 | .667 | .670 | .673 |
| 12 | .676 | .679 | .682 | .685 | .688 | .691 | .694 | .697 | .700 | .703 |
| 13 | .705 | .708 | .711 | .714 | .716 | .719 | .722 | .724 | .727 | .729 |
| 14 | .732 | .734 | .737 | .739 | .742 | .744 | .746 | .749 | .751 | .754 |
| 15 | .756 | .758 | .760 | .763 | .765 | .767 | .769 | .771 | .774 | .776 |
| 16 | .778 | .780 | .782 | .784 | .786 | .788 | .790 | .792 | .794 | .796 |
| 17 | .798 | .800 | .801 | .803 | .805 | .807 | .809 | .811 | .812 | .814 |
| 18 | .816 | .818 | .819 | .821 | .823 | .824 | .826 | .828 | .829 | .831 |
| 19 | .832 | .834 | .835 | .837 | .839 | .840 | .842 | .843 | .845 | .846 |
| 20 | .847 | .849 | .850 | .852 | .853 | .854 | .856 | .857 | .858 | .860 |
| 21 | .861 | .862 | .864 | .865 | .866 | .867 | .869 | .870 | .871 | .872 |
| 22 | .874 | .875 | .876 | .877 | .878 | .879 | .880 | .882 | .883 | .884 |
| 23 | .885 | .886 | .887 | .888 | .889 | .890 | .891 | .892 | .893 | .894 |
| 24 | .895 | .896 | .897 | .898 | .899 | .900 | .901 | .902 | .903 | .904 |
| 25 | .905 | .906 | .906 | .907 | .908 | .909 | .910 | .911 | .912 | .912 |

Table 3.--Estimation of site index

| Tree No. | D.b.h. (X) | Height (Y) | $1-e^{-aX}$ | $Y-4.5$ | $\dfrac{Y-4.5}{1-e^{-aX}}=h_i$ | $h_i(1-e^{-14a})$ | Estimated site index |
|---|---|---|---|---|---|---|---|
| USING INDIVIDUAL TREE DATA |||||||| 
| 1 | 12.9 | 66 | 0.703 | 61.5 | 87.48 | 64.02 | 68.5 |
| 2 | 12.2 | 55 | .682 | 50.5 | 74.05 | 54.20 | 58.7 |
| 3 | 10.0 | 57 | .609 | 52.5 | 86.21 | 63.11 | 67.6 |
| 4 | 11.5 | 56 | .661 | 51.5 | 77.91 | 57.03 | 61.5+ |
| 5 | 13.0 | 55 | .705 | 50.5 | 71.63 | 52.43 | 56.9 |
| 6 | 13.3 | 60 | .714 | 55.5 | 77.73 | 56.90 | 61.4 |
| 7 | 15.9 | 69 | .776 | 64.5 | 83.12 | 60.84 | 65.3 |
| 8 | 15.1 | 65 | .758 | 60.5 | 79.82 | 58.43 | 62.9 |
| 9 | 13.0 | 60 | .705 | 55.5 | 78.72 | 57.62 | 62.1 |
| 10 | 12.2 | 57 | .682 | 52.5 | 76.98 | 56.35 | 60.8 |
| 11 | 12.1 | 62 | .679 | 57.5 | 84.68 | 61.99 | 66.5 |
| 12 | 12.1 | 63 | .679 | 58.5 | 86.16 | 63.07 | 67.6 |
| 13 | 13.4 | 63 | .716 | 58.5 | 81.70 | 59.80 | 64.3 |
| 14 | 12.7 | 62 | .697 | 57.5 | 82.50 | 60.39 | 64.9 |
| 15 | 12.1 | 56 | .679 | 51.5 | 75.85 | 55.52 | 60.0 |
| 16 | 10.8 | 61 | .638 | 56.5 | 88.56 | 64.83 | 69.3 |
| 17 | 13.7 | 62 | .724 | 57.5 | 79.42 | 58.14 | 62.6 |
| 18 | 13.2 | 61 | .711 | 56.5 | 79.47 | 58.17 | 62.7 |
| 19 | 13.6 | 61 | .722 | 56.5 | 78.25 | 57.28 | 61.8 |
| 20 | 14.5 | 70 | .744 | 65.5 | 88.04 | 64.44 | 68.9 |
| 21 | 11.3 | 53 | .654 | 48.5 | 74.16 | 54.29 | 58.8 |
| Sum | 268.6 | 1274 | -- | --. | -- | --- | 1333.1 |
| Sum of squares | 3473.60 | -- | -- | -- | -- | -- | 84886.01 |
| Arith. mean | -- | 60.67 | -- | -- | -- | -- | 63.48 |
| Average square | 165.4095 | -- | -- | -- | -- | -- | -- |

ALTERNATIVE METHOD BASED ON AVERAGE TREE

Mean d.b.h. $(\bar{X}) = \sqrt{165.4095} = 12.86$

Thus, if $a = 0.094$, $1 - e^{-aX} = 1 - e^{-0.094(12.86)} = 0.702$

Then $\bar{Y} - 4.5 = 60.67 - 4.5 = 56.17$

and $(\bar{Y} - 4.5) \big/ (1 - e^{-aX})$ becomes $56.17 \big/ 0.702 = 80.009$

the site index is: $4.5 + \dfrac{(\bar{Y} - 4.5)\ (1 - e^{-14a})}{1 - e^{-aX}}$

which at $1 - e^{-14a} = 0.732$ means site index is $4.5 + 80.009\,(0.732)$ or $4.5 + 58.57 = 63.07$

CALCULATION OF SAMPLING ERROR FROM INDIVIDUAL TREE DATA

$$s^2 = \frac{\sum d^2}{n-1} = \frac{84886.01 - \dfrac{(1333.1)^2}{21}}{21 - 1} = \frac{259.55239}{20} = 12.977615, \text{ and } S = 3.60$$

$$s_{\bar{X}} = \frac{S}{\sqrt{n}} = \frac{3.60}{\sqrt{21}} = 0.786$$

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comparison with the variation among dominant trees of the same stand.

A similar comparison was made for five other stands, with essentially the same results. In no case did the difference between the two methods exceed 0.80 foot. The recommended procedure, therefore, is to compute the average height and the square root of the average square of d.b.h. of all trees in the stand. These averages are then used in the five steps sketched above to estimate site index for the stand.

## The Sampling Error

In fitting the equation, the square of the standard error of estimate was derived as 30.087... by pooling the variance within diameter classes with that arising from deviations of the class means from the fitted equation. The

Table 4.--Computed standard errors[1] of the mean, in feet of height, in relation to mean diameter and sample size

| D.b.h. (inches) | Number of observations | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 4 | 9 | 16 | 25 | 36 | 49 |
| 10 | 5.49 | 2.76 | 1.85 | 1.40 | 1.14 | 0.96 | 0.84 |
| 11 | 5.49 | 2.75 | 1.84 | 1.39 | 1.12 | 0.94 | 0.82 |
| 12 | 5.49 | 2.75 | 1.83 | 1.38 | 1.11 | 0.93 | 0.80 |
| 13 | 5.49 | 2.74 | 1.83 | 1.37 | 1.10 | 0.92 | 0.79 |
| 14 | 5.49 | 2.74 | 1.83 | 1.37 | 1.10 | 0.91 | 0.78 |
| 15 | 5.49 | 2.74 | 1.83 | 1.37 | 1.10 | 0.92 | 0.79 |
| 16 | 5.49 | 2.75 | 1.84 | 1.38 | 1.11 | 0.93 | 0.80 |
| 17 | 5.49 | 2.76 | 1.85 | 1.40 | 1.13 | 0.95 | 0.83 |
| 18 | 5.50 | 2.76 | 1.86 | 1.41 | 1.15 | 0.98 | 0.86 |
| 19 | 5.50 | 2.77 | 1.88 | 1.43 | 1.18 | 1.01 | 0.89 |
| 20 | 5.51 | 2.78 | 1.90 | 1.46 | 1.20 | 1.04 | 0.93 |
| 21 | 5.52 | 2.80 | 1.92 | 1.49 | 1.24 | 1.09 | 0.98 |
| 22 | 5.53 | 2.82 | 1.95 | 1.53 | 1.28 | 1.13 | 1.03 |
| 23 | 5.54 | 2.83 | 1.98 | 1.56 | 1.33 | 1.18 | 1.08 |
| 24 | 5.55 | 2.86 | 2.01 | 1.60 | 1.38 | 1.24 | 1.14 |
| 25 | 5.56 | 2.88 | 2.03 | 1.65 | 1.43 | 1.29 | 1.20 |

[1]Computed from $S_{yx} \sqrt{1/n + \dfrac{x^2}{\Sigma x^2}}$

standard error of estimate is the square root of this pooled variance or 5.485... feet. This applies to single trees in the vicinity of the mean. However, the site index of a stand should be based on the measurement of a number of trees.

Therefore we are more concerned with the standard errors of estimate for means at various average diameters, and based on varying numbers of observations. Table 4 was prepared to fill this need.

Study of this table reveals that a sampling error of the mean of about 1 foot with a confidence level of about 2 in 3 results from a sample of 30 trees for the usual range of d.b.h. of dominant red spruce. The sampling errors of table 4 were calculated by using all the 912 trees that were measured for this study, stratified only by d.b.h. classes and adjusted for the average correlation of d.b.h. and height.

In selecting stands, a broad range in site quality was deliberately sought. Thus it is likely that there will be less variation among trees of a single stand than for the 32 stands as a whole. This was the case in the stand used in table 3. Here the standard deviation was estimated as 3.6 and the standard error of the mean was 0.786 with 21 observations. Thus where an accuracy of about 1 foot is sought, with P = 2/3, a sample of 20 to 30 trees from a stand should suffice.

# Appraisal

A METHOD of gaging site quality for red spruce has been developed. Certain assumptions were made and then mathematical operations were used to develop the measure. Before it can be recommended for general use, however, it must be examined and appraised in the light of available tests or other criteria.

Tests
Of A Site Index

Review of the literature has failed to reveal any tests or standards for a measure of site quality. As pointed

out earlier, the interest in measuring site quality arises from the need to classify forest lands on the basis of productive capacity. To adequately answer this need it is evident that if other factors are equal, site index should be strongly correlated with increment. A strong correlation will exist when variations in one factor (site index) are associated with variations in the other (increment), and when the unexplained residual differences from the fitted equation are relatively small. This situation is more likely to occur when there is a clear cause-and-effect relationship, and when errors of measurement are small.

If the same stand is measured repeatedly over a period of several years, and at each measurement the calculated site index differs from those obtained earlier, it is evident that our site index is subject to an appreciable measurement error. In such a situation the correlation between site index and increment is bound to be weaker than if repeated measurements result in the same calculated index. Thus stability is an essential attribute of any system of measuring site quality.

If a series of stands are measured and site index is determined for each, differences in site index should correspond with differences in productive capacity. This raises two questions: (1) Is total height of dominant red spruce 14 inches d.b.h. (or any other specified diameter) consistent as a measure of productive capacity? (2) Is the formula used to adjust to equivalent height at 14 inches d.b.h. correct? Data are not now available that would answer those questions. The proposed method of measuring site quality must be considered as tentative until adequate tests have provided conclusive answers.


Reasonableness

In the absence of direct tests of strength of correlation between site index and increment, it then becomes necessary to consider the proposed method and establish whether it is reasonable and in agreement with common experience. A rough test of this technique may be made by comparing estimates of site index for particular stands with evidence given by descriptive information. Conclusions as to site quality drawn from this evidence would be based on the knowledge and impressions of men who have studied the distribution and growth habits of the species. The 32 stands

used in preparing this measure of site index were so compared.

The three most important forest types in which red spruce occurs are the spruce-hardwood slopes, spruce flats, and spruce swamps.[4] These three classes were first recognized and described by Cary (1896). He mentioned that much of the spruce occurs on what is really hardwood land where "... it is common knowledge among lumbermen, are found the largest and finest spruce trees." The nearly pure softwood forest typical of somewhat shallower, less well-drained

Table 5.--Site index of red spruce related to
descriptive site classes

(Each "X" represents one study area.)

| Site index (height at 14 inches d.b.h.) | Site I | Site II | Site III |
|---|---|---|---|
| 70 | X | -- | -- |
| 69 | -- | -- | -- |
| 68 | -- | -- | -- |
| 67 | XX | -- | -- |
| 66 | XX | X | -- |
| 65 | X | -- | -- |
| 64 | XXX | XX | -- |
| 63 | -- | XXX | -- |
| 62 | X | XX | -- |
| 61 | -- | XX | X |
| 60 | -- | XX | XX |
| 59 | -- | -- | XX |
| 58 | -- | -- | X |
| 57 | -- | X | X |
| 56 | -- | -- | -- |
| 55 | -- | -- | X |
| 54 | -- | -- | X |

soils and often gently rolling "flats" represents an intermediate site quality for spruce. Flat, poorly-drained, moss-covered soils constitute poor sites. They support stands somewhat similar in composition to those on intermediate sites. "Spruce may stand thickly in such land," Cary said, "but the growth of the trees is slow, and they do not reach their maximum size."

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[4]The so-called 'spruce slope' type is not considered here. It was originally important in the mountainous sections of the spruce-fir region, but it has been widely cut over and what remains is now largely restricted to mountain tops and steep slopes inaccessible for logging and of value principally for watershed protection.

Subsequently a number of investigators have confirmed and elaborated upon Cary's observations about site quality of spruce, among them being Hosmer (1902), Woodward (1913), Murphy (1917), Westveld (1930), Heimburger (1934), and Donahue (1940).

From the descriptive data recorded at the time the stands were selected for study, each area was classified as site I, II, or III according to whether it was most nearly represented a spruce-hardwood slope, a spruce flat, or a spruce swamp. The site index for each stand, as determined in this study, was then plotted on a vertical scale under the appropriate site class. The resulting distribution (table 5) reveals a good correlation between the quantitative and qualitative measures of site for this species.

It is not to be expected that a simple site classification based only upon cover type and topographic position will invariably and correctly express true site quality. Too many other important factors are omitted. Hence there is some overlapping of site classes. But the trend of site-index values is evident, and it provides support for the proposed method on the grounds that the results are reasonable.

The results were also confirmed by evidence from indicator plants. Some of the site-types described by Heimburger (1934, 1941) and Westveld (1951) were used to indicate good, medium, and poor sites for red spruce, as follows:

Site I   : Viburnum and Viburnum-Oxalis types

Site II  : Cornus-Maianthemum and Oxalis-Cornus types

Site III : Hylocomium and Cornus types.

All but four of the stands, which could not be put in any of the above types, were grouped and plotted in the same manner as described above. Results were similar, except that there was a little more overlapping, and agreement was not so close. Average site index was 66, 63, and 59 for Site I, II, and III respectively.

Other
Factors

If height-over-diameter is to be used to estimate site quality, it must be recognized that other factors may

affect this relationship.    For it to be useful, therefore, we need to know what other factors  may be important and how to define our stands so as to minimize  the effects of these extraneous factors.

Stand density  is perhaps  the most obvious  of these other factors.  Low density may stimulate growth in diameter and thus impair tree form, which tends to lower total height in relation to d.b.h.  On the other hand, diameter growth in seriously overstocked stands is often reduced and would have the opposite effect on the height-d.b.h. relationship.    The influence of density can be minimized  by avoiding the obvious extremes of overstocking and understocking.

The release effect  afforded by cutting  would influence both height and diameter growth, probably to an unequal and varying degree.    Therefore  it is necessary  to select trees   that   have been  in a  dominant  position  for a long enough time  that the effect of site  will have become dominant in the height-diameter ratio.  At least 25 years should have elapsed since a dominant tree appears  to have been released  either  by cutting  or mortality  of large  adjacent trees.    This can be determined fairly conclusively by examining  the surrounding area  for  old stumps,  dead trees or stubs,  and by  taking  increment cores  and  checking  ring growth for signs of release.

Among   factors   most   likely   to   influence   diameter growth alone are the length and apparent vigor of the crown. To reduce variability  from this cause,  only dominant trees with a crown ratio of 0.4 or better should be used. Furthermore, decadent,  deformed trees,  those having damaged tops, and those of very poor crown vigor must be avoided.

This does not exhaust  the possible causes  of variations in height-diameter relations.  But it is believed that those remaining elements  that may exert  some influence are mostly of minor importance, are only occasionally operative, or can be recognized and eliminated.  Overmaturity of sample trees, very local site differences,  and differential effect of  hardwood  vs.  softwood  competition  on the form of red spruce are some examples.    However, the forest manager must be alert  to the possible influence  of these and other factors.    Should the relationship of total height to d.b.h. be affected,  it would be necessary to limit the measurement of site quality to stands that were not affected.

In the spruce-fir region  red and white spruce,  hemlock,  and  balsam fir--all tolerant species--are  important components of the commercial forest.  The site index that is proposed  is  for  red spruce;  and the  question  naturally arises  as to whether  it might apply  to the other tolerant species.   Numerical expression of site quality for tolerant species in  all-aged,  mixed stands  has always presented  a difficult mensurational problem.   If the  system suggested here  can be adapted  to other species,  in this region  and elsewhere, it may be of great help to forest managers, ecologists, and soils men.

It is unlikely that the index itself would accurately describe site quality of other species.  Differences in form and in response to site variation are almost certain to mean different curves for different species.   On the other hand, the  method employed  should be  as useful  for one tolerant species as another.   This presumes  that the shape  of the curve describing the relationship  of height to diameter  of dominant trees  is reasonably constant  for a given species, and that  total height  for a  given d.b.h.  is sensitive to changes in site quality.

It seems likely  that  the  more tolerant  and longer lived hemlock  would be more adaptable  to this method  than the shortlived fir or the less tolerant white spruce.   The susceptibility of fir to decay  should be taken into account when classifying site for this species. White spruce, having a fast growth rate  and being less able to survive  for long periods under suppression,  might lend itself to the conventional height-age approach.   Tolerant hardwoods--beech and sugar maple,  and to a lesser extent  yellow birch--probably would have one advantage  over red spruce  in any site index system.   They commonly have a much wider range  in height. Where  average extremes  of height  for  dominant red spruce were found  in this study  to be  55 and 75 feet,  hardwoods commonly ranged from 55 to 100 feet.   Accurate height measurement of hardwoods  is much more difficult,  however,  because of the rounded or irregular-shaped tops.

# Recommendations

**T**HE METHOD of appraising site quality for red spruce that has been described has passed such tests as we have been able to devise. Nevertheless, it must be regarded as tentative until it has been tried more extensively. The questions of accuracy with respect to yields, stability over a long period of time, and consistency when applied over various parts of a species' commercial range need to be explored. We therefore recommend and urge foresters concerned with stands of red spruce to try it out and test it as data permit.

Forest managers may find this method practical for appraising the suitability of stands that now support mature red spruce, for continued management of that species. It also provides a means for segregating and mapping spruce stands in terms of site quality for management purposes. Thus the efforts of small woodlot owners or others interested in quality spruce production can be more effectively directed toward growing high-value veneer logs or sawlogs; for site I spruce has greater potentialities for such products by reason of both its ultimate greater size and its better form. This method is presently serving as a base against which to test the relative importance of various soil properties and topographic features in influencing site quality. Since this site-index system provides a continuous numerical measure of site, it can also be used as the dependent variable in regression and correlation analyses.

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